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Reliability MURI Contributions to Industrial Reliability Efforts

Kurt V. Smith PhD

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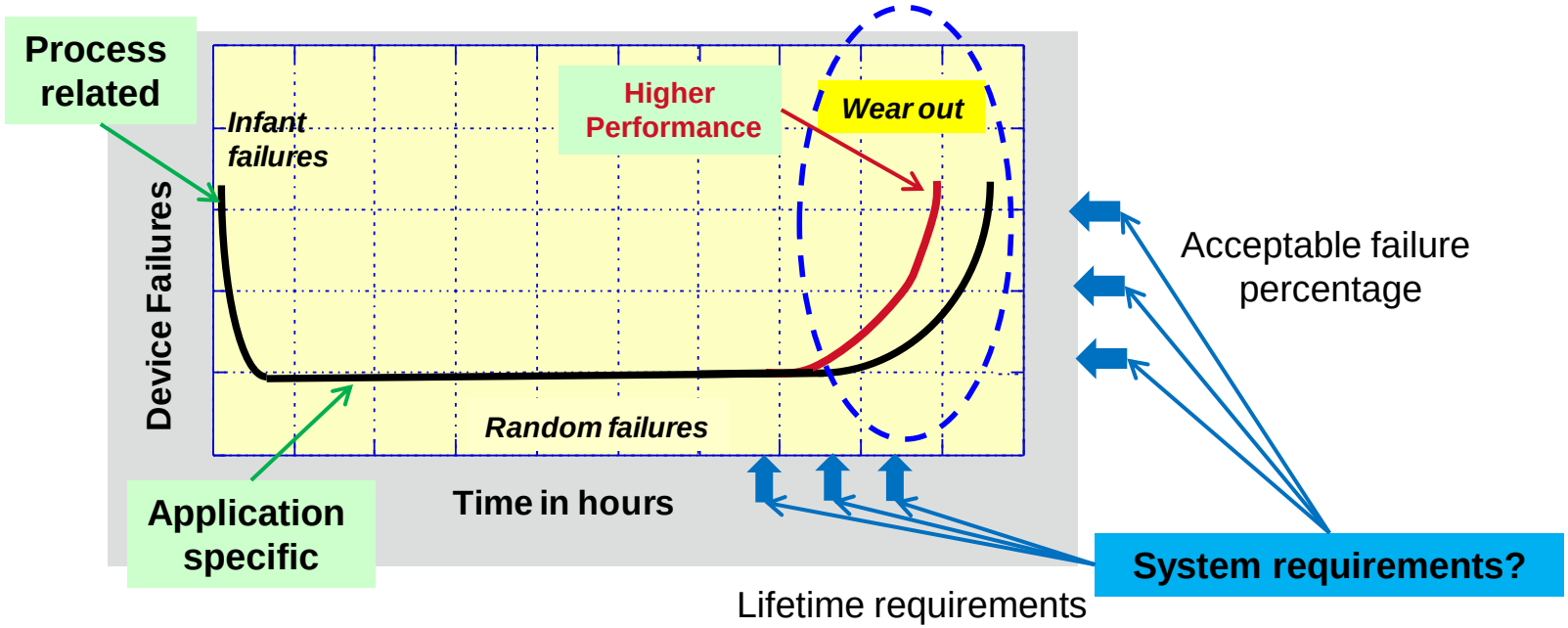
Outline

- Introduction
- Current test protocols
  - Results
  - Limitations
- Reliability predictions process
  - Identifying mechanisms
  - Physics of failures
  - Projecting Lifetime from accelerated testing
- Summary

The Reliability Question

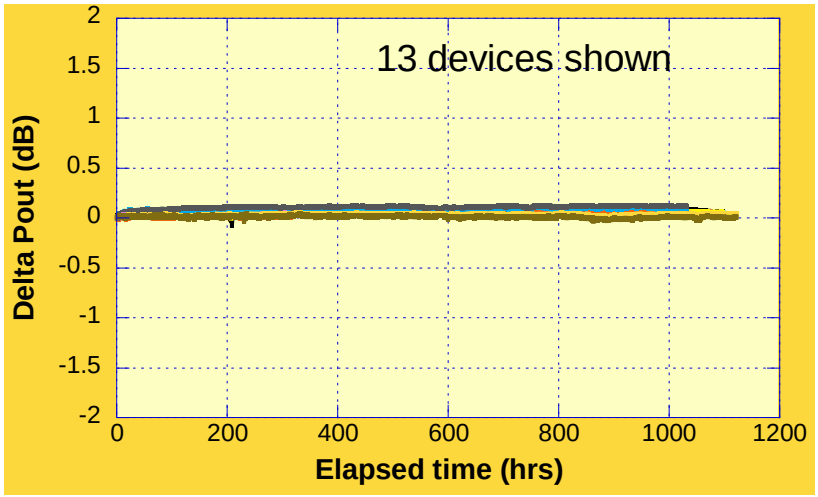
Reliability typically interpreted as efforts to predict wear out region of life curve

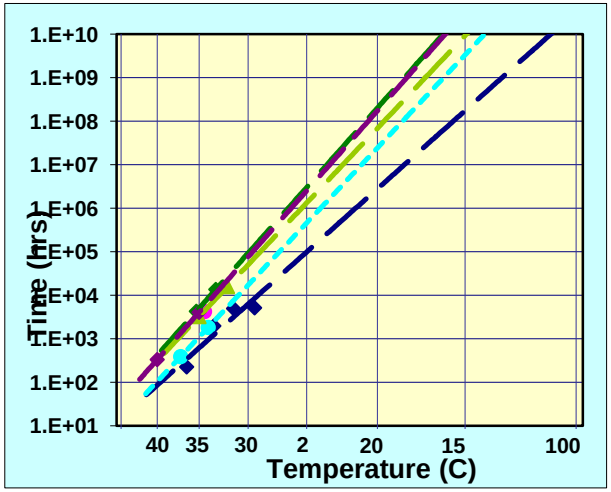


Reliable parts are those that meet the operational requirements of a particular application

Current Reliability Test Protocols

- **RF operational life test (RFOLT) is "long" term testing at use conditions**
  - **Non-predictive test**
- **High Temperature DC Testing used to extrapolate lifetimes**
  - **Based only on temperature acceleration**



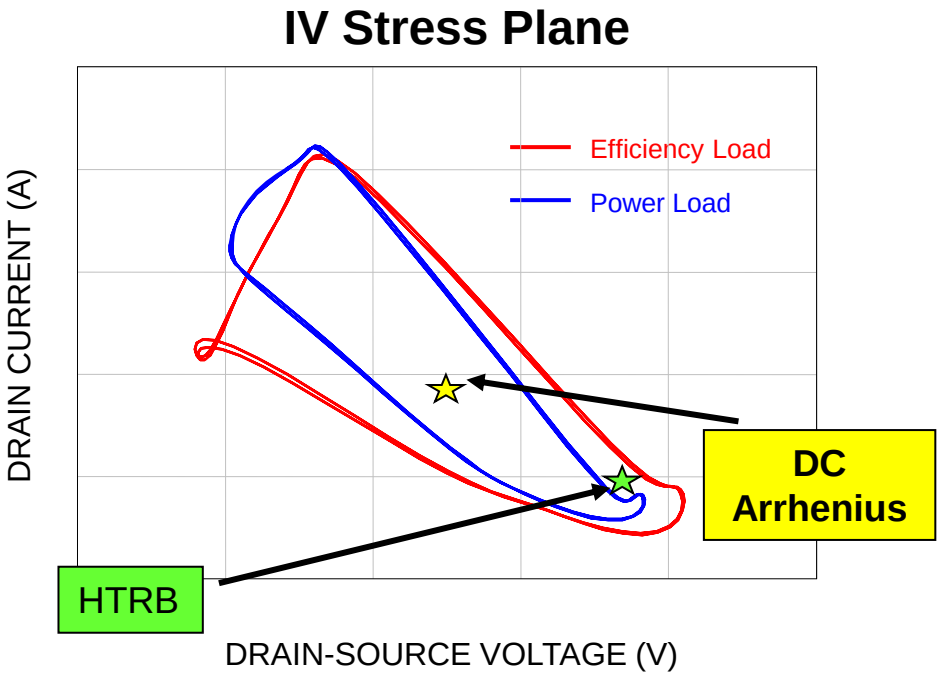


- **Data from GaN process at Raytheon**
  - **Similar data has been taken and available for pHEMT and MHEMT**

Procedures have qualified 100,000's of reliable devices in multiple material systems

How Can Reliability Projections Be Enhanced?
RF Device Specific

- During RF cycle, the IV stress plane is a function of multiple factors
  - Quiescent bias
  - Compression
  - Load
  - Temperature
- Current and voltage extremes can exceed limits of common accelerated tests
  - Gate current can reach relatively high levels
- Extrapolations made solely from temperature acceleration



Predictive models beyond Arrhenius would be useful

Generalized Reliability Equation

In any reliability test there are three stress factors, which can be accelerated

$$MTTF = C * AF(I) * AF(V) * AF(T)$$

where C is a constant and AF() is an acceleration factor

- *Ideally factors are independent*
  - Most likely interdependent
- High Temperature DC testing using an Arrhenius model is special case
  - Current held constant, voltage changes very little in test
  - Degradation mechanism follows Arrhenius model

$$MTTF = C' \exp\left(\frac{-E_a}{\kappa T}\right) \quad \text{where} \quad C' = C * AF(I) * AF(V)$$

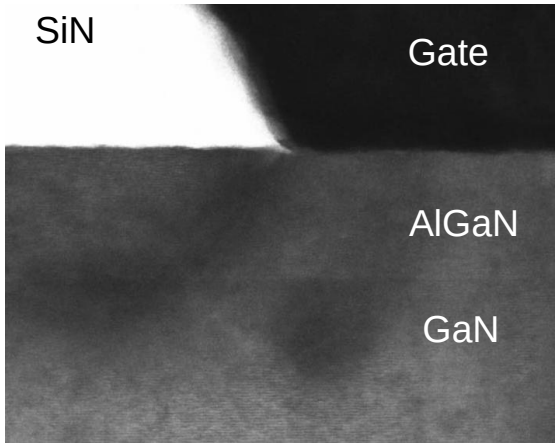
More accurately the AF's are known, the better the extrapolated lifetimes can be predicted (for example)

$$TTF = A_o V^{-b} J^{-N} \exp\left(\frac{-E_a}{\kappa T}\right)$$

Understanding all acceleration factors necessary for accurate projections

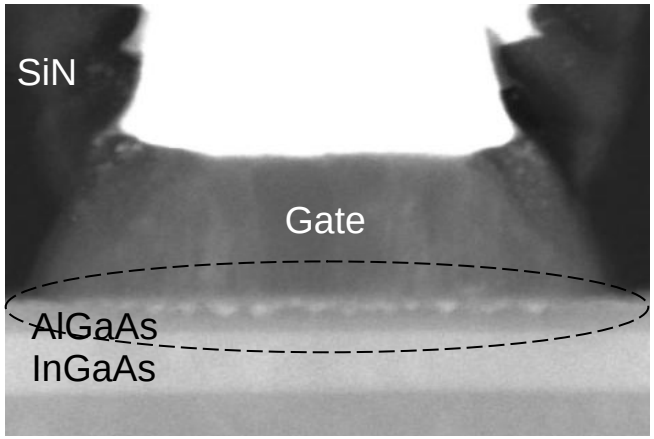
First Step: Identifying Physical Degradation Mechanisms

Nitride Defect Creation
GaN Limiting Mechanism



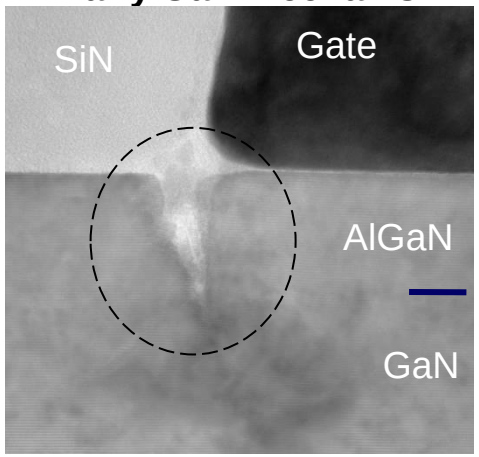
- **Hot electron created defects in nitride/surface**
- **Trap related**
- **Has exponential dependence in trap creation**
  - **Follows Arrhenius**

Gate Sinking
MHEMT Limiting Mechanism



- **Diffusion of metal into semiconductor**
  - **Follows Arrhenius**

Lattice Disruption
Early GaN Mechanism

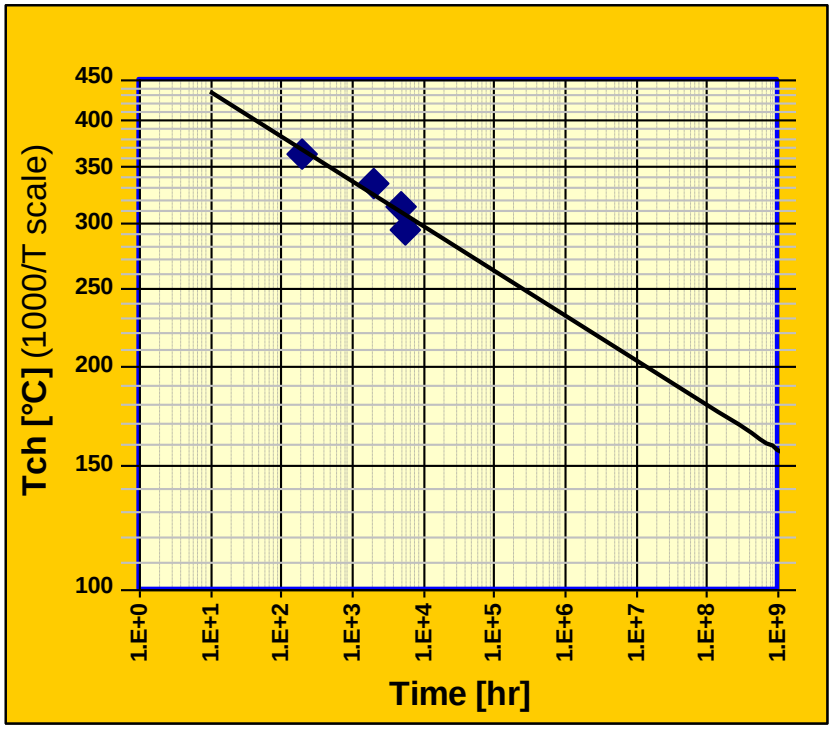


Shown not cause
- **Strain dominated**
  - **Non-Arrhenius**

Actual cause
- **Electrochemical reaction**
- **Diffusion limited**
  - **Follows Arrhenius**

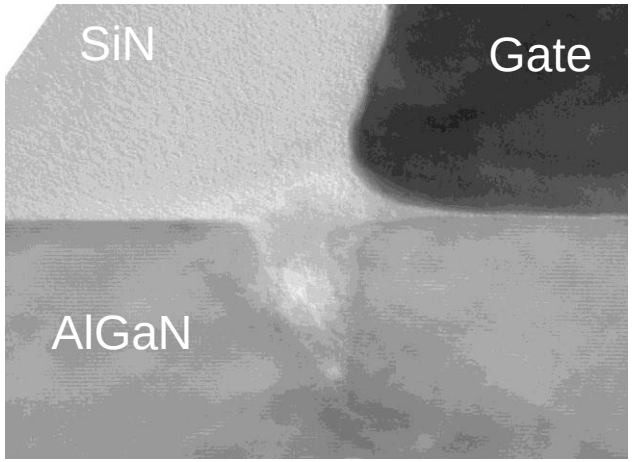
Identifying physical degradation mechanisms are only a start

Example of Mechanism to Lifetime Projection: Identifying Mechanism



- **Early GaN devices from 2004**
  - **Not representative of current process**
- **Device lifetime >10^9hrs @ 150°C**
  - **28V HT DC testing**

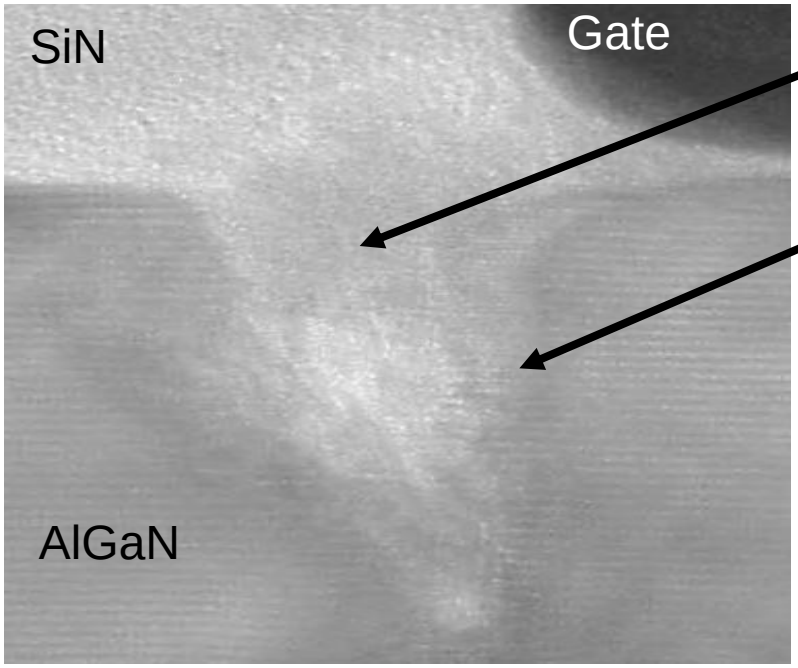
Valid analysis?



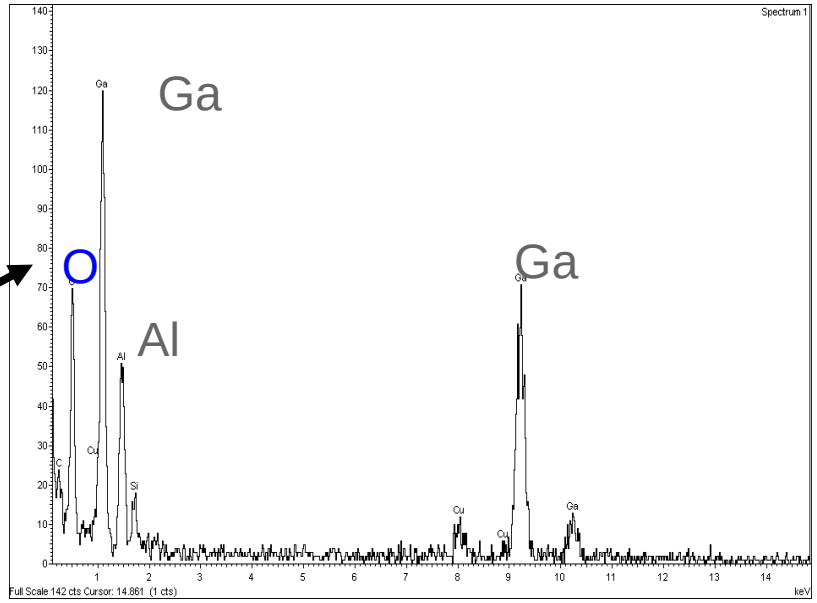
- **X-sectional TEM indicated substantial changes in crystal structure at the edge of gate**
  - **Most severe at drain side of gate**

Understanding degradation mechanism ensures proper reliability predictions

Example of Mechanism to Lifetime Projection: Understanding the Mechanism



- **Variation in gray scale indicates material in the disruption**
  - **Not a crack or void**
- **Partial lattice network extending into/ through the disruption**

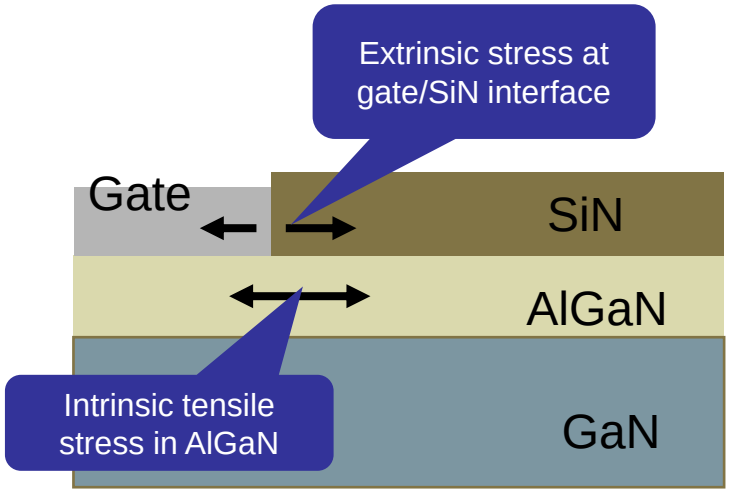


- **ESCA indicates presence of impurities**
  - **Oxygen is detected in defect area**
  - **No Oxygen is detected in areas beyond defect region**

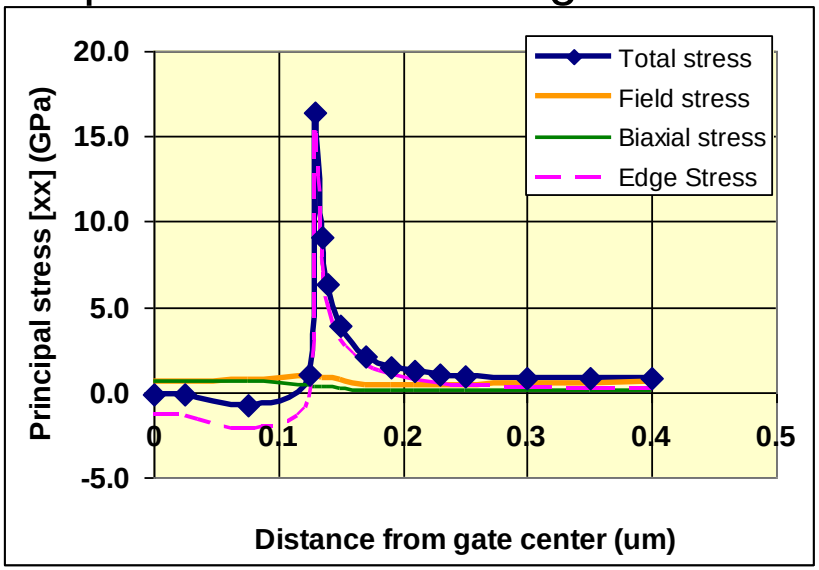
Physical evidence provides clues to mechanism

Example of Mechanism to Lifetime Projection: Acceleration Factors - Voltage

- **Voltage may influence Lattice Disruptions through polarization**
  - **Field would create force on fixed charges resulting in stress**
    - **Inverse-piezo stress reported by Joh, etal**
- **Stress is also result of 2 other major components**
  - **Biaxial stress due to lattice mismatch**
  - **Edge stress due to CTE mismatch**
    - **Process induced**
    - **Temperature dependent**



Total stress is dominated by process-induced edge stress



- **Total effective stress will be reduced as the temperature increases which is contrary to experimental results**

Voltage not the primary driver of Lattice Disruptions

Example of Mechanism to Lifetime Projection: Acceleration Factors - Temperature

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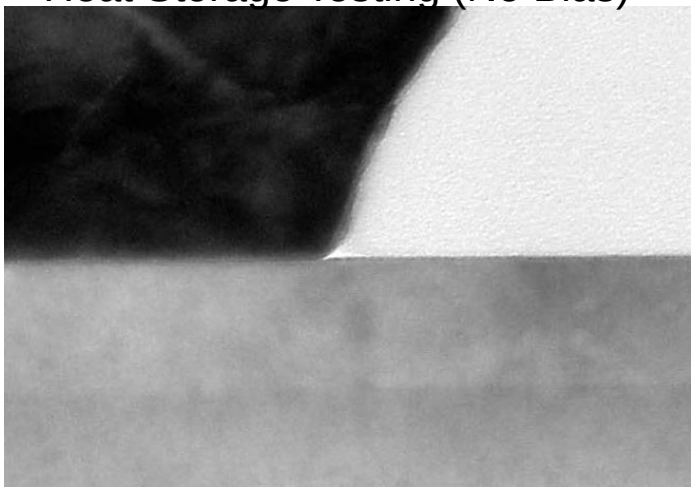
- **Increasing temperature may influence LD's through 2 major effects**
  - **Reducing stress due to CTE mismatches**
    - **Counter to experimental results**
  - **Enhancing diffusion of impurities**

Heat Storage Testing (No Bias)



- **Device tested for 3000hrs at 350ºC**
  - **Wafer showed LD's under HT DC testing**
- **Edge and Biaxial stress are still present**
- **No indication of Lattice Disruptions**

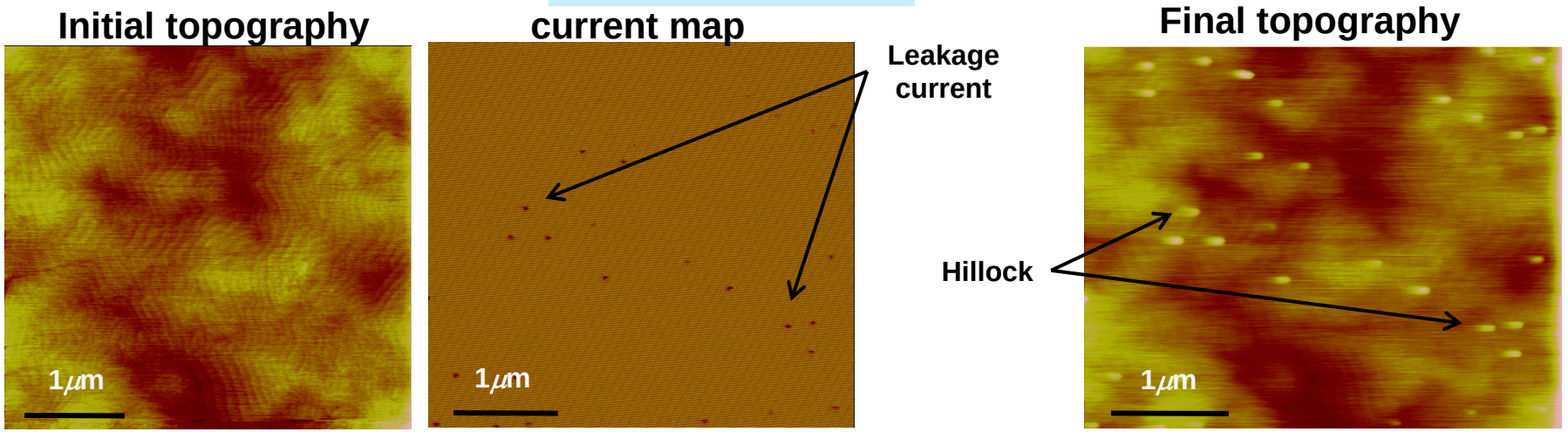
- **Lack of lattice disruptions points to a bias dependence of mechanism**
  - **Field creation of defects is unlikely**
    - **Inverse-piezo would not exceed the edge stress reduction**
    - **Direct defect creation would require large amounts of energy**

Stress and temperature are not sufficient for LDs

Example of Mechanism to Lifetime Projection: Acceleration Factors - Current

- Current can induce changes in materials through electrochemical interactions

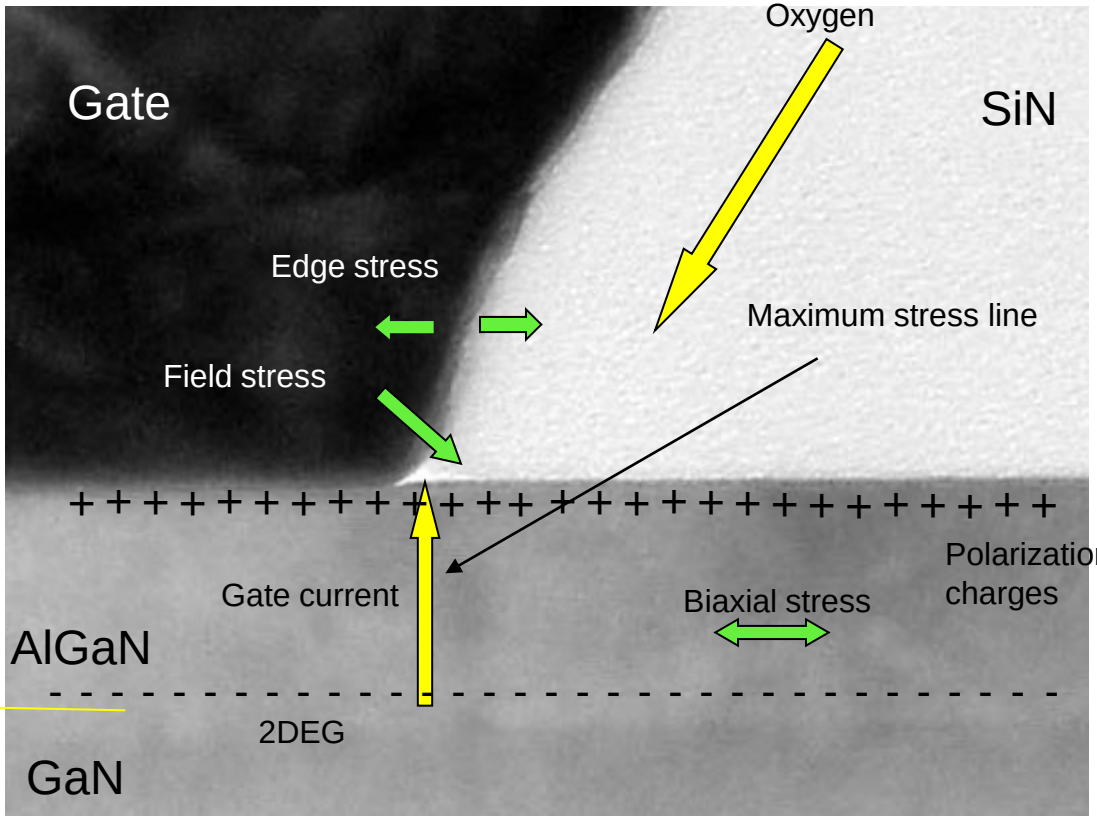
Conductive AFM



- Results courtesy of E. Yu, etal
  Published in Miller, E. et al APL, Vol 82(8), 1293 (2003)
- Topography and current map taken together
- Second topography scan shows oxide hillocks created by first scan
  - At areas of high leakage current
  - No leakage noted in second scan

Electrochemical oxidation demonstrated in AlGaN

Example of Mechanism to Lifetime Projection: Proposed Physical Model



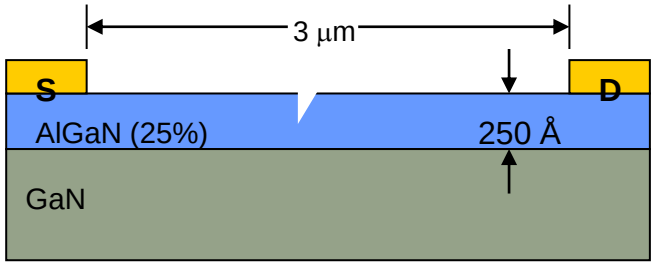
- **Combined stresses produce**
  - **path for gate current**
  - **Weak area for etching**
- **Oxygen (contaminant) diffuses to surface**
  - **Temperature accelerates**
- **Current and contaminant combine to change material**
  - **Anodization-type behavior**

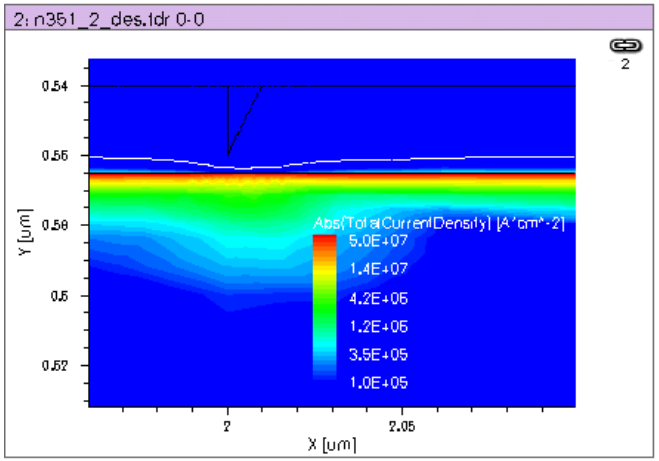
- **Process expected to be diffusion limited**
  - **Expected to follow Arrhenius model; consistent with measured data**

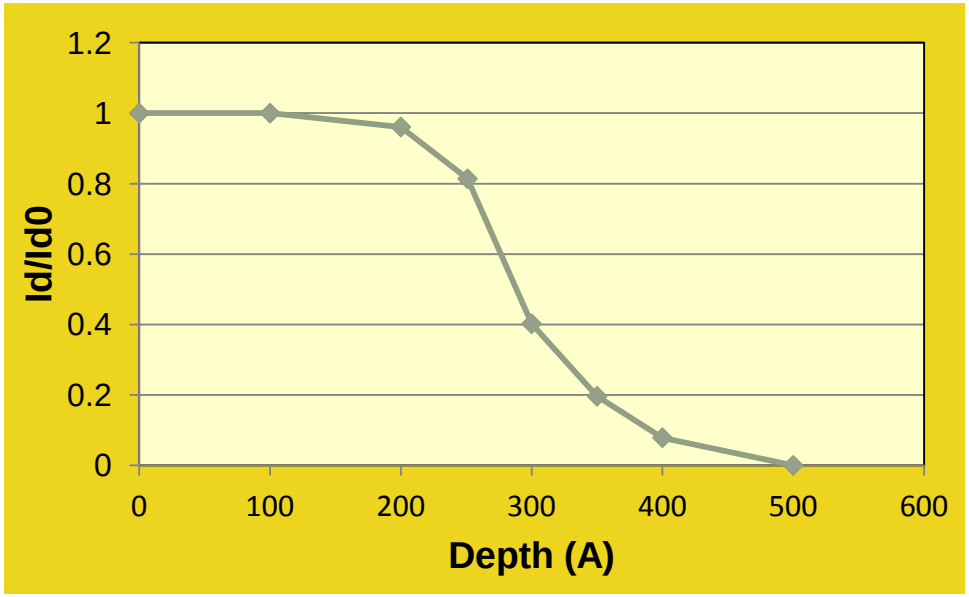
Analysis supports an Arrhenius model for predictions

Example of Mechanism to Lifetime Projection: Verifying Mechanism

- Lattice disruption grows linearly, but current is interrupted only when disruption breaks the 2DEG
  - Current drops modeled using TCAD







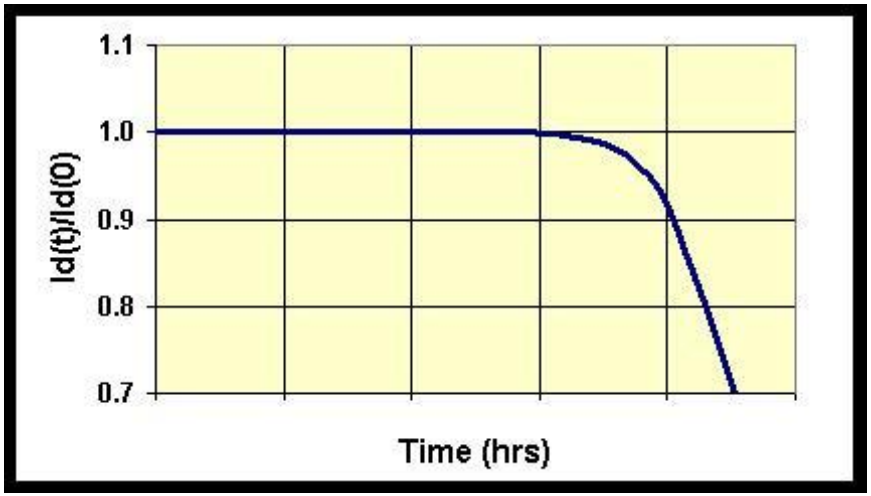
- Current not substantially affected until LD impinges on channel
  - Small changes would

TCAD model suggests a method of tracking evolution of mechanism

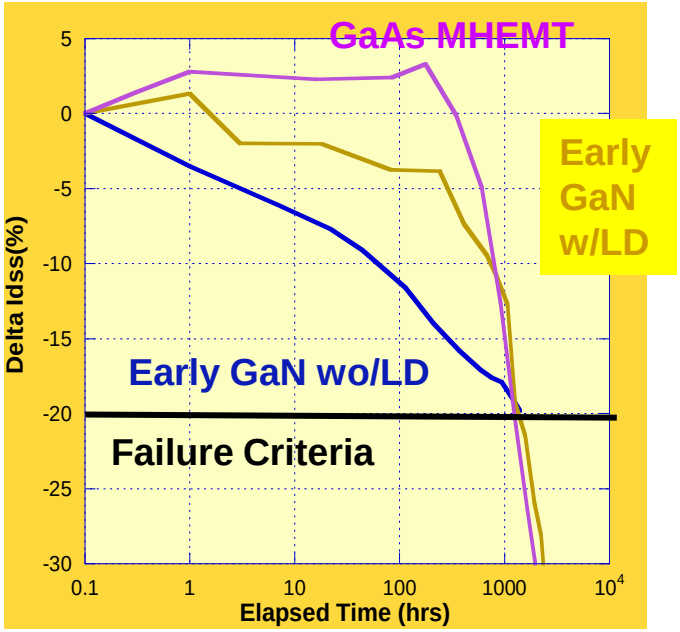
Example of Mechanism to Lifetime Projection: Verifying and Tracking Mechanism

- **Modeling mechanism predicts evolution of current drop with time**
  - **Tracking experimental data provides early look at mechanism**

Modeled Behavior



Experimental Data



- **All examples showing similar lifetimes with differing degradation mechanisms**
  - **Electrical response radically different**
  - **Failure analysis has verified differences in degradation mechanism**

Comparing modeled and experimental data provides validation

Summary

- **Reliability predictions based on RFOL and high temperature DC have supported 100000's of successfully fielded parts**
- **Enhancing reliability projections beyond temperature acceleration would be useful**
- **Process for validating a reliability projection requires multiple steps**
  - **Identifying the physical mechanism**
  - **Understanding interaction of the mechanism and all acceleration factors**
  - **Determining the limiting factor and model needed to make projections**
  - **Validation of model**
- **Demonstrated process on early GaN failure mechanism – Lattice Disruptions**
  - **Current limiting mechanism in GaN is nitride defect creation**